NASA/CR-2001-211252
ICASE Report No. 2001-37

# Common-path Heterodyne Laser-induced Thermal Acoustics for Seedless Laser Velocimetry

*Roger C. Hart*
*ICASE, Hampton, Virginia*

*G.C. Herring and R. Jeffrey Balla*
*NASA Langley Research Center, Hampton, Virginia*

December 2001

## The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATIONS. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- Email your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Telephone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/CR-2001-211252
ICASE Report No. 2001-37

# Common-path Heterodyne Laser-induced Thermal Acoustics for Seedless Laser Velocimetry


*Roger C. Hart*
*ICASE, Hampton, Virginia*

*G.C. Herring and R. Jeffrey Balla*
*NASA Langley Research Center, Hampton, Virginia*

*ICASE*
*NASA Langley Research Center*
*Hampton, Virginia*

*Operated by Universities Space Research Association*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199



Prepared for Langley Research Center
under Contract NAS1-97046

December 2001

Available from the following:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

# COMMON-PATH HETERODYNE LASER-INDUCED THERMAL ACOUSTICS FOR SEEDLESS LASER VELOCIMETRY

ROGER C. HART*, G. C. HERRING†, AND R. JEFFREY BALLA‡

**Abstract.** We demonstrate the use of a novel technique for the detection of heterodyne laser-induced thermal acoustics signals, which allows the construction of a highly stable seedless laser velocimeter. A common-path configuration is combined with quadrature detection to provide flow direction, greatly improve robustness to misalignment and vibration, and give reliable velocity measurement at low flow velocities. Comparison with Pitot tube measurements in the freestream of a windtunnel shows root-mean-square errors of 0.67 m/s over the velocity range 0 – 55 m/s.

**Key words.** LITA, laser velocimetry, laser anemometry, laser-induced thermal acoustics

**Subject classification.** Experimental Fluid Dynamics .

**1. Introduction.** Non-intrusive optical methods for measuring fluid flow velocity are of great importance to the experimental fluid dynamics and aerodynamics communities. However, the only optical velocimetry methods to have found wide use, laser doppler velocimetry [1] and particle image velocimetry [2], require the introduction of small (~ 1 μm diameter) seed particles into the flow to serve as light scatterers. Seeding is not feasible in some wind tunnels due to concerns over removal of spent seed, clogging of flow-straightening screens, or abrasion of finely polished surfaces. Additionally, there are regions in airflows of interest, such as vortices over delta wings or behind leading-edge slats, where useful seed concentrations are difficult or impossible to achieve. Thus a need exists for a seedless laser velocimetry method. Previous work has demonstrated the potential of laser-induced thermal acoustics (LITA) to fill this need [3-6]. However, none of the approaches employed so far for heterodyne detection appears suitable for routine use in environmentally adverse windtunnel environments by workers who are not highly skilled optics researchers. Here we demonstrate a novel means of implementing LITA velocimetry that has the intrinsic stability and robustness to allow the construction of a useful, fieldable instrument.

**2. Theory of LITA Signal Detection.** LITA is a pump-probe process: a pump laser creates a periodic perturbation in the medium, which serves to diffract the beam of a probe laser to a detector. In our apparatus the beam of a Q-switched Nd:YAG laser operating at wavelength $\lambda_{pump}$ = 1064 nm is split by a 50/50 beamsplitter to produce two pump beams which are made to focus and cross at a single point at angle $2\theta = 1.4^{\circ}$ by a lens (Fig. 2.1).

* ICASE, NASA Langley Research Center, Hampton, VA 23681-2199, e-mail: rchart@icase.edu. This research was supported by the National Aeronautics and Space Administration under NASA Contract No. NAS1-97046 while the author was in residence at ICASE, NASA Langley Research Center, Hampton, VA 23681-2199.
† AMDB, NASA Langley Research Center, Hampton, VA 23681-2199.
‡ AMDB, NASA Langley Research Center, Hampton, VA 23681-2199.

Interference fringes of period $\Lambda = \lambda_{pump}/2\sin\theta$ are formed at the beam intersection. As the laser wavelength is not resonant with any absorptive transition in the medium (air) the only optical interaction is electrostriction, which creates two counter-propagating acoustic waves or gratings traveling in the $\pm\hat{x}$ direction at speed of sound $v_S$ with respect to the medium. The acoustic wavelength is equal to the optical fringe spacing and the frequency $f_B = v_S / \Lambda$ is about 7.8 MHz at room temperature. The beam of the CW probe laser at wavelength $\lambda_{probe} = 532$ nm

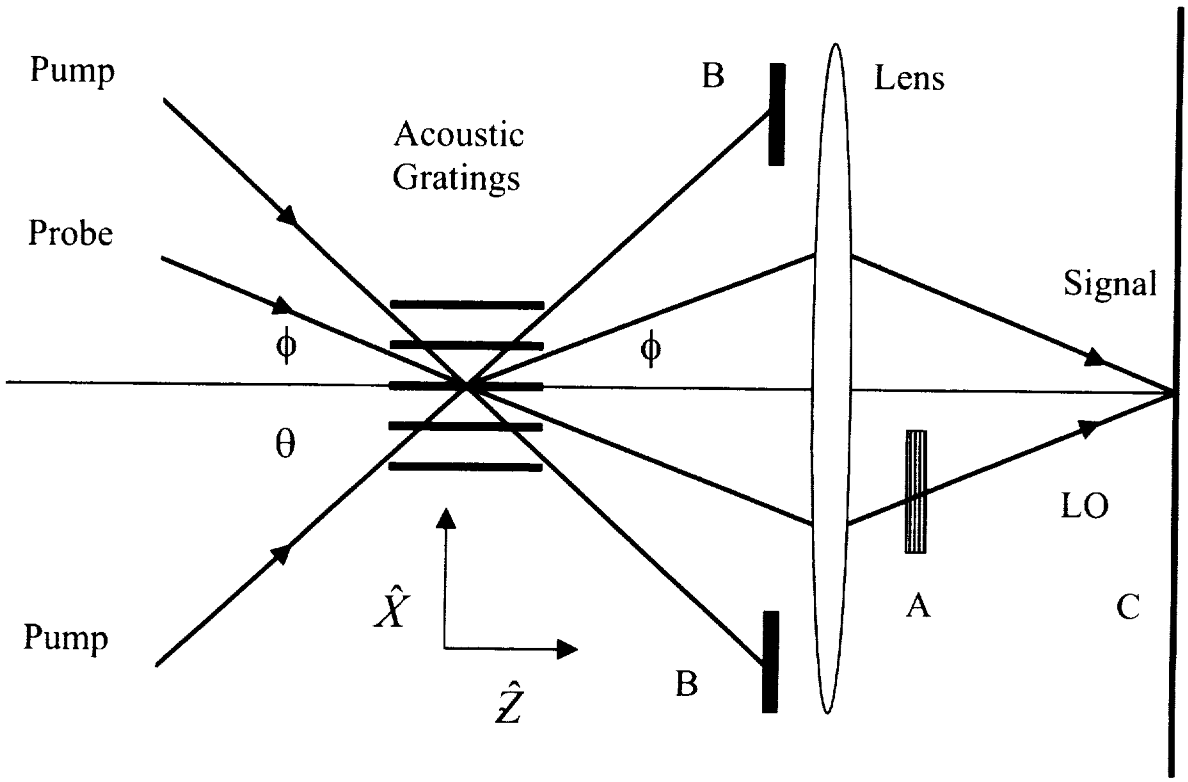


FIG. 2.1. *Beam crossing geometry and schematic of detection scheme. A: attenuator; B: beamstop; C: Focal/detector plane; LO: local oscillator beam.*

is incident on the waves at the Bragg or phase-matching angle $\phi$ where $\Lambda = \lambda_{probe}/2\sin\phi$. The signal beam is diffracted at angle $\phi$ (Fig. 2.1) with Doppler shifts $\Delta\omega_+ = -\vec{q}\cdot(\vec{v}_{con} - \vec{v}_S)$ and $\Delta\omega_- = -\vec{q}\cdot(\vec{v}_{con} + \vec{v}_S)$ due to the motion of the gratings, where $\vec{v}_{con}$ is the flow velocity, $\vec{v}_S = v_S\hat{x}$, and $\vec{q} = q\hat{x}$ is the acoustic grating vector with $q = 2\pi/\Lambda$.

**2.1. Collinear Local Oscillator Method.** The simplest implementation of LITA velocimetry (not shown) requires the introduction of a local oscillator (LO) beam collinear with the signal with the same frequency $\omega$ as the probe. The field is

(2.1) $$A(t) = A_{LO}\exp(i\omega t) + A_S e^{-\beta t}\left(\exp(i(\omega + \Delta\omega_- t)) + \exp(i(\omega + \Delta\omega_+ t))\right) + c.c.,$$

where $A_{LO}$ and $A_S$ are the real amplitudes respectively of the LO and signal beams, $\beta = \alpha\, v_S$ with $\alpha$ the acoustic amplitude absorption coefficient [7], and *c.c.* means complex conjugate. Averaging over a time long compared to the optical period but short compared to $1/f_B$ and integrating over the area of the beams, the time dependence of the detected power is

$$P(t) = A_{LO}^2 + 2A_{LO}A_S e^{-\beta t}\left[\cos(\Delta\omega_- t) + \cos(\Delta\omega_+ t)\right], \tag{2.2}$$

where we assume $A_{LO} >> A_S$ for shot-noise-limited detection and so neglect the term $\propto A_S^2$. Neglecting also the DC term, the real part $\tilde{P}_R(\tilde{\omega})$ of the Fourier transform of $P(t)$ is a sum of four Lorentzians

$$\tilde{P}_R(\tilde{\omega}) = 2A_{LO}A_S\left[\frac{\beta}{\beta^2 + (\tilde{\omega} \pm \Delta\omega_-)^2} + \frac{\beta}{\beta^2 + (\tilde{\omega} \pm \Delta\omega_+)^2}\right], \tag{2.3}$$

with peaks at $\pm\Delta\omega_-$ and $\pm\Delta\omega_+$. Although the Doppler shifts are signed quantities, the detected heterodyne signal contains information only on the absolute values. Analysis (*e.g.* discrete Fourier transform or time domain fitting via Levenburg-Marquardt or Prony's method [6]) of real-valued data described by Eq. 2.2 thus allows independent determination only of $|\Delta\omega_-|$ and $|\Delta\omega_+|$, yielding $v_S$ and $|v_F|$, where $v_F = \hat{q}\cdot\vec{v}_{con}$ is the component of flow velocity along $\hat{q}$.

Laboratory evaluation of this collinear LO method of implementing LITA velocimetry [6] revealed the following disadvantages: 1) proper alignment of the LO and signal beams is difficult to achieve and maintain; 2) the apparatus is very sensitive to vibration since the signal and LO beam must follow different paths on different optics; 3) no direct means of determining flow direction is available since only the absolute values of $\Delta\omega_-$ and $\Delta\omega_+$ are available as shown above; 4) both accuracy and precision are very poor for flow velocities less than ~20 m/s due to the difficulty of accurately discriminating the nearly degenerate frequencies $|\Delta\omega_-|$ and $|\Delta\omega_+|$ in the presence of noise. Although various technical means of ameliorating these difficulties are available, this approach seemed unsuitable to be the basis of a robust instrument with a useful velocity dynamic range.

**2.2. Grating Demodulation with Quadrature Detection.** A solution to these four problems was found with two modifications: a non-collinear geometry, and quadrature detection. A lens recrosses and refocuses the signal and attenuated probe beams in plane C (Fig. 2.1.). Assuming for simplicity unit magnification, the field at C is

$$\begin{aligned} A(t) = {} & A_{LO}\exp\left(i\left(\vec{k}_{LO}\cdot\vec{r} - \omega t\right)\right) + \\ & A_S e^{-\beta t}\exp\left(i\left(\vec{k}_S\cdot\vec{r} - (\omega + \Delta\omega_-)t\right)\right) + \\ & A_S e^{-\beta t}\exp\left(i\left(\vec{k}_S\cdot\vec{r} - (\omega + \Delta\omega_+)t\right)\right) + c.c., \end{aligned} \tag{2.4}$$

where $\vec{k}_{LO}$ and $\vec{k}_S$ are the wavevectors for LO and signal beams with $\left|\vec{k}_{LO,S}\right| = 2\pi/\lambda_{probe}$. With $\left|\vec{k}_{LO} - \vec{k}_S\right| = q$ (due to the phase matching between pump and probe), and neglecting the term $\propto A_S^2$, the intensity in plane C is then

(2.5) $$I(x,t) = A_{LO}^2 + 2A_{LO}A_S e^{-\beta t}\left[\cos(qx + \Delta\omega_- t) + \cos(qx + \Delta\omega_+ t)\right],$$

which describes interference fringes of spatial period $\Lambda$ traveling at speeds $\Delta\omega_+/q = v_F - v_s$ and $\Delta\omega_-/q = v_F + v_s$; that is, *the lens produces an image of the acoustic waves.* No modulation at frequencies $\Delta\omega_-$ and $\Delta\omega_+$ would be seen by a broad-area detector (width >> $\Lambda$) placed at C. However, if a series of slits (*e.g.* a Ronchi ruling) parallel to the fringes with period $\Lambda = 2D$ is placed on the surface of the detector (Fig. 2.2) the modulation is recovered as bright fringes pass alternately across transparent and opaque regions. We refer to this detection scheme as grating demodulation. Taking advantage of the equal periodicities of the fringes and the Ronchi ruling, the time dependence of the detected power *P(t)* may be written

(2.6) $$P(t) = F\int_a^{a+D} I(x,t)\,dx$$

where $F$ is a constant accounting for the number of fringes and the height of the beams, and $a$ specifies the transverse location (phase) of the ruling with respect to an arbitrary origin (Fig. 2.2). After some manipulation one finds

(2.7) $$\begin{aligned} P(t) &= bA_{LO}^2 \\ &- 2cA_{LO}A_S e^{-\beta t}\left(\sin(\varphi)\cos(\Delta\omega_- t) + \cos(\varphi)\sin(\Delta\omega_- t)\right) \\ &- 2cA_{LO}A_S e^{-\beta t}\left(\sin(\varphi)\cos(\Delta\omega_+ t) + \cos(\varphi)\sin(\Delta\omega_+ t)\right), \end{aligned}$$

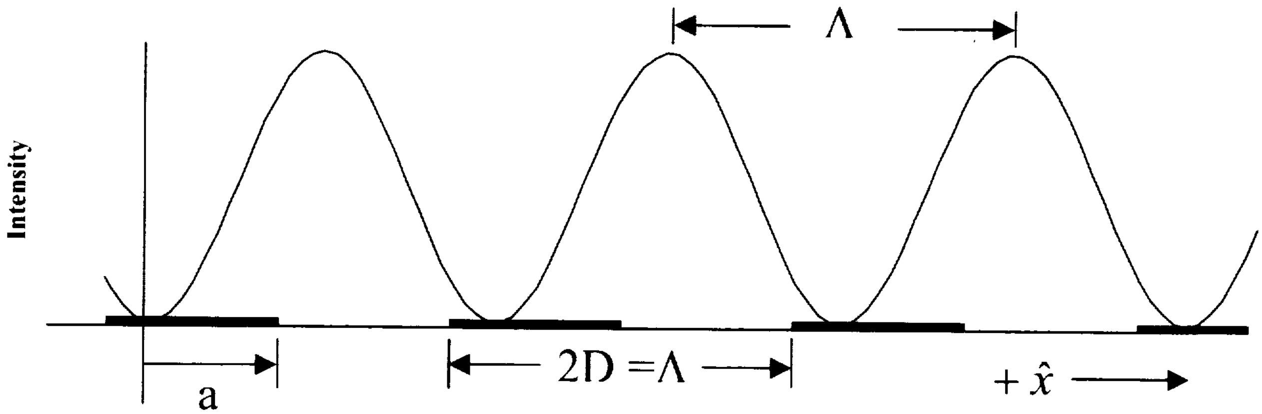


FIG. 2.2. *Plane C in Fig. 2.1 showing Ronchi ruling (thick lines) and one traveling fringe pattern.*

where $\varphi = \pi a/D$ and $b$ and $c$ are constants. Thus by shifting the ruling transverse to the optical axis (changing $a$) the phase of the modulation in the signal may be varied; *this is equivalent to shifting the phase of the local oscillator*. This provides a convenient means for implementing dual-channel phase-sensitive detection with two phases of the LO differing by 90°, known as quadrature detection. If the converging signal and LO beams (Fig. 1) are divided by a suitable beamsplitter so that two separate beam intersections are formed on two separate rulings and detectors, then by setting the relative transverse shift between the rulings to $\Lambda/4$ both quadrature components of the signal may be recovered simultaneously. That is, for channel $P_0(t)$ let $a = 3D/2$ in Eq. 2 and for channel $P_{90}(t)$ $a = D$, giving

(2.8)
$$P_0(t) = bA_{LO}^2 + 2cA_{LO}A_S e^{-\beta t}\left(\cos(\Delta\omega_- t) + \cos(\Delta\omega_+ t)\right),$$
$$P_{90}(t) = bA_{LO}^2 + 2cA_{LO}A_S e^{-\beta t}\left(\sin(\Delta\omega_- t) + \sin(\Delta\omega_+ t)\right).$$

Forming the complex signal $Z(t) = P_0(t) + iP_{90}(t)$, we find the real part of the Fourier transform now consists of only two Lorentzians

(2.9)
$$\widetilde{Z}_R(\widetilde{\omega}) = 2cA_{LO}A_S\left[\frac{\beta}{\beta^2 + (\widetilde{\omega} - \Delta\omega_-)^2} + \frac{\beta}{\beta^2 + (\widetilde{\omega} - \Delta\omega_+)^2}\right]$$

with peaks at $\Delta\omega_-$ and $\Delta\omega_+$. Thus analysis of *Z(t)* can recover the sign as well as magnitude of the Doppler shifts (Fig. 2.3). For $v_F = 0$ the spectral peaks occur at $\widetilde{\omega} = \pm q v_S = \pm\omega_B = \pm 2\pi f_B$; as $v_F$ varies the peaks will shift simultaneously towards more positive or more negative frequency (depending on the flow direction) but will maintain the separation $2\omega_B$. Flow and sound velocities are found as $v_F = (\Delta\omega_- + \Delta\omega_+)/2q$ and $v_S = (\Delta\omega_+ - \Delta\omega_-)/2q$. Note that Mach number $M = v_F/v_S$ is independent of $q$, so if flow temperature and thus

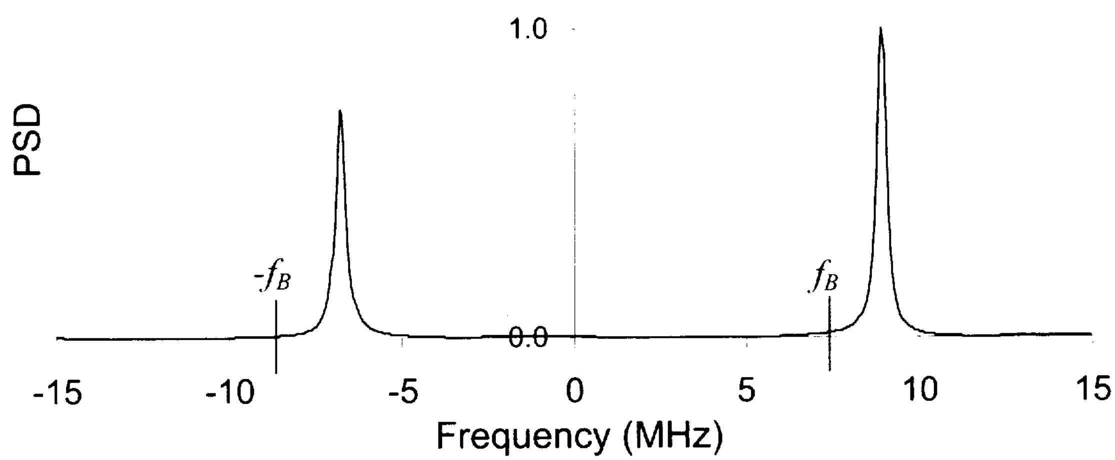


FIG. 2.3. *Experimental power spectral density (PSD) of single-shot LITA waveform taken using grating demodulation and quadrature detection. Flow velocity $v_F$ = 45 m/s, and $f_B$ = 7.8 MHz.*

$v_S$ are known $v_F$ may be found without calibration of $\Lambda$.

This grating demodulation/quadrature detection scheme remedies the defects found in the collinear LO method. Since signal and LO beams are incident on the same optics (common path), detection is *intrinsically* stable against both misalignment and vibration. Flow direction is found directly. Resolution at low velocities is greatly improved since the frequencies $\Delta\omega_-$ and $\Delta\omega_+$ are no longer nearly degenerate.

**3. Experimental Results.** A compact velocimeter employing this detection scheme was used at NASA Langley Research Center's Basic Aerodynamics Research Tunnel to map the flow behind a rearward-facing step [8]. As part of this program, multiple comparisons of freestream velocity $V_{LITA}$ (average of ~350 shots) measured by LITA with freestream velocity $V_{Pitot}$ measured by Pitot tube were acquired (Fig. 3.1). Defining error as $V_{Pitot}$-$V_{LITA}$, the root-mean-square error (RMSE) of this data set is 0.67 m/s. For $V_{Pitot}$ > 30 m/s and for $V_{Pitot}$ = 0, the RMSE is < 0.4 m/s, while for intermediate velocities RMSE is 0.84 m/s. Note that a velocity of 1 m/s corresponds here to a Doppler shift of 23 kHz in a carrier frequency of 5.6 x $10^{14}$ Hz.

We have demonstrated an elegant, intrinsically stable means of performing heterodyne LITA velocimetry with quadrature detection that will allow the construction of a robust seedless laser velocimeter.

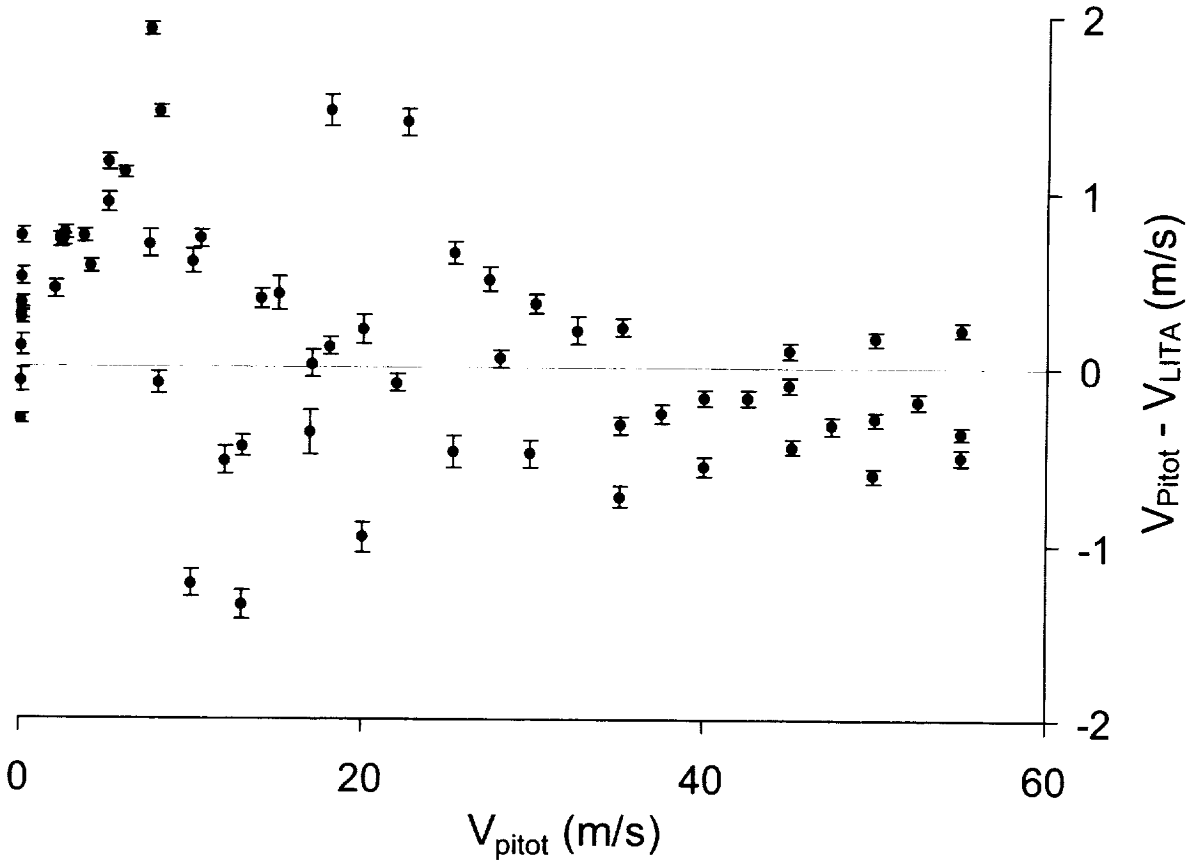


FIG. 3.1. *Error $V_{Pitot}$-$V_{LITA}$ for measurements in windtunnel freestream. Error bars show one standard deviation of the mean.*

We wish to acknowledge the invaluable assistance of Mark Fletcher and Luther Jenkins in carrying out the windtunnel measurements.

# REFERENCES

[1] T. DURRANI AND C. GREATED, *Laser Systems in Flow Measurements*, Plenum Press, New York, 1977.

[2] M. RAFFEL, C. WILLERT, AND J. KOMPENHANS, *Particle Image Velocimetry – A Practical Guide*, Springer, New York, 1998.

[3] D. WALKER, R. WILLIAMS, AND P. EWART, *Thermal Grating Velocimetry*, Opt. Lett. **23** (1998), p. 1316.

[4] S. SCHLAMP, E. CUMMINGS, AND T. SOBOTA, *Laser-induced thermal acoustic velocimetry with heterodyne detection*, Opt. Lett. **25** (2000), p. 224.

[5] B. HEMMERLING, D. KOZLOV, AND A. STAMPANONI-PANARIELLO, *Temperature and flow-velocity measurements by use of laser-induced electrostrictive gratings*, Opt. Lett. **25** (2000), p. 1340.

[6] R. HART, R. BALLA , AND G. C. HERRING, *Simultaneous velocimetry and thermometry of air by use of nonresonant heterodyned laser-induced thermal acoustics*, App. Opt. **40** (2001), p. 965.

[7] L. KINSLER, A. FREY, A. COPPENS, AND J. SANDERS, *Fundamentals of Acoustics*, Wiley & Sons, New York, 1982.

[8] R. HART, J. BALLA, G. HERRING, AND L. JENKINS, *Seedless Laser Velocimetry using Heterodyne Laser Induced Thermal Acoustics*, 19th International Congress on Instrumentation in Aerospace Facilities, Cleveland, OH; also available as ICASE Report No. 2001-19, NASA Langley Research Center, Hampton, VA 23681-2199, 2001.

# REPORT DOCUMENTATION PAGE

*Form Approved OMB No. 0704-0188*



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
December 2001

**3. REPORT TYPE AND DATES COVERED**
Contractor Report

**4. TITLE AND SUBTITLE**
Common-path heterodyne laser-induced thermal acoustics for seedless laser velocimetry

**5. FUNDING NUMBERS**
C NAS1-97046
WU 505-90-52-01

**6. AUTHOR(S)**
Roger C. Hart, G.C. Herring, and R. Jeffrey Balla

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
ICASE
Mail Stop 132C
NASA Langley Research Center
Hampton, VA 23681-2199

**8. PERFORMING ORGANIZATION REPORT NUMBER**
ICASE Report No. 2001-37

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-2199

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA/CR-2001-211252
ICASE Report No. 2001-37

**11. SUPPLEMENTARY NOTES**
Langley Technical Monitor: Dennis M. Bushnell
Final Report
To be submitted to Optics Letters.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified–Unlimited
Subject Category 34
Distribution: Nonstandard
Availability: NASA-CASI (301) 621-0390

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

We demonstrate the use of a novel technique for the detection of heterodyne laser-induced thermal acoustics signals, which allows the construction of a highly stable seedless laser velocimeter. A common-path configuration is combined with quadrature detection to provide flow direction, greatly improve robustness to misalignment and vibration, and give reliable velocity measurement at low flow velocities. Comparison with Pitot tube measurements in the freestream of a windtunnel shows root-mean-square errors of 0.67 m/s over the velocity range 0-55 m/s.

**14. SUBJECT TERMS**
LITA, laser velocimetry, laser anemometry, laser-induced thermal acoustics

**15. NUMBER OF PAGES**
12

**16. PRICE CODE**
A03

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | | |

NSN 7540-01-280-5500

Standard Form 298(Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102